

# Crossing Vortex Lattices in Layered Superconductors

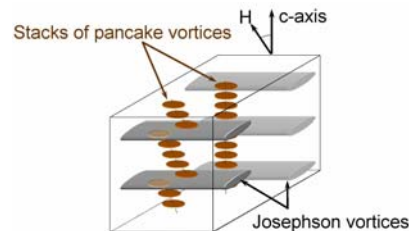
A. Koshelev<sup>a</sup>, V. Vlasko-Vlasov<sup>a</sup>, U. Welp, W. Kwok<sup>a</sup>, G. W. Crabtree<sup>a</sup>, J.M. Hiller<sup>a</sup>, and K. Kadowaki<sup>b</sup>

<sup>a</sup> Materials Science Division, Argonne National Laboratory

<sup>b</sup> University of Tsukuba, Japan

## Motivation

- Unique **crossing-lattices** state in strongly anisotropic layered superconductors ( $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$ ): **Josephson vortices (JVs)** + **pancake-vortex (PVs)** stacks
- Interplay between energy and length scales  $\rightarrow$  multiple competing states and rich dynamic properties
  - challenge for theory and experiment
- Possibility to manipulate one sublattice using another sublattice  $\rightarrow$  vortex electronics

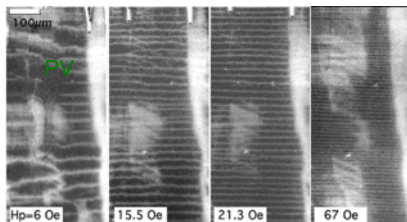


## Recent Achievements

### Magneto-optical imaging of Josephson vortex lattice using "decoration" by pancake stacks

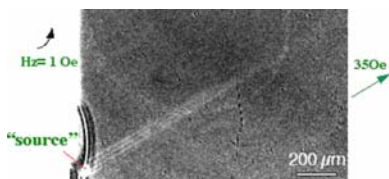
PV stacks form chains along JVs  
First observed by decorations  
Bolle *et al.*, PRL **66**, 112 (1991)

Evolution of the JV lattice with increasing in-plane field,  $H_z=2\text{Oe}$



JV lines order and their period decreases as  $(\gamma\Phi_0/B_x)^{1/2}$  with increasing  $B_x$

"Beaming" of flux along the JVs from surface defect

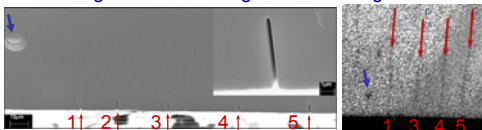


Pancake vortices nucleate at the defect site and channel along JVs

### Manipulating pancake flux using Josephson vortices + artificial patterning

- The PVs can be manipulated with JVs:
  - The JVs  $\rightarrow$  **easy channels** for PV stacks.
  - Moving JVs are capable of dragging PV stacks
- "Flux-manipulation" magneto-optical experiments in FIB patterned BSCCO crystals.

Channeling of PV flux along JVs from the gates



Artificial gates prepared by FIB

**Challenge:** controlled delivery of PV stacks to desired locations with single flux-quantum resolution

### Vortex-chain states and phase transitions

Vortex chains are formed at small c-axis fields  $B_z=0.1-3\text{ G}$

- Competition between two factors:
  - JVs tear apart pancake stacks
  - Magnetic coupling aligns pancake stacks
- Relative strength: London length  $\lambda(T)$  vs Josephson length  $\lambda_J$

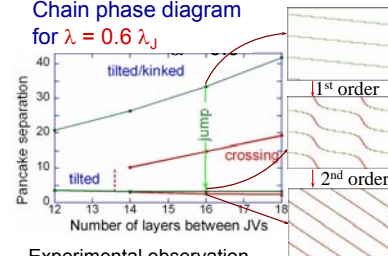
### Limiting Configurations

Crossing Chains

Tilted Chains



### Chain phase diagram for $\lambda = 0.6 \lambda_J$

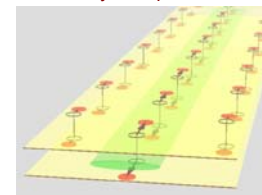


Experimental observation of the 1<sup>st</sup> order transition:  
A. Grigorenko *et al.*, Nature **414**, 728 (2001).

### In-plane vortices inside dense PV lattice:

From Josephson vortices to solitons  $B_z=10-100\text{ G}$

Displacements of pancake vortices Induced by Josephson vortex



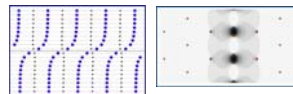
### In-plane vortex evolves with decreasing anisotropy:

- Large anisotropies, JV-like core:** PVs have small displacements with respect to the aligned positions, JV core covers many pancake rows



Displacements in the central row Phase difference between two central layers

- Smaller anisotropies, soliton-like core:** large pancake displacements in the central row, the core shrinks to one pancake row

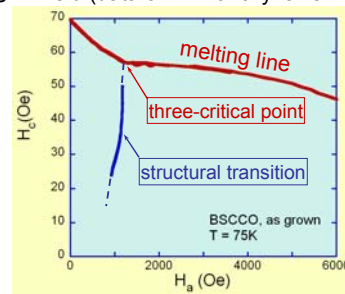


## Future directions

### Phase diagram in tilted fields at moderate anisotropies

- Different lattices and their realization in the parameter space
  - Crossing lattices
  - Soliton lattice
  - Tilted lattice
  - Composite lattice built from vortex rows tilted at different angles
- Interpretation of observed three-critical point: Melting line crossing structural phase transition. (collaboration with M. Konczykowski (Ecole Polytechnique) and K. Kadowaki (Univ. of Tsukuba))

BSCCO phase diagram in tilted field (data of M. Konczykowski)



1. V. K. Vlasko-Vlasov, A. E. Koshelev, U. Welp, G. W. Crabtree, and K. Kadowaki, Phys. Rev. B **66**, 014523 (2002)

2. A. E. Koshelev, Phys. Rev. B **68**, 094520 (2003); Phys. Rev. B **71**, 174507 (2005)